SECTION THREE

DETERMINATION OF THE GRAVITY FIELD

3.0 INTRODUCTION

The methods of geoid determination involve gathering gravity over a wide area, mostly through surface and airborne gravity measurements. Significant progress has been made over the last decade since the initiation of the geoid project in Malaysia by JUPEM. This progress can be seen in terms of the gravity data collection (from just 2000 points in 1989 to over 10000 points in 2000), the computation algorithm (Stokes integral, LSC, FFT) and the evaluation of results (use of GPS data, satellite altimetry). However, up to now, there is no precise geoid available yet for Malaysia and its surrounding seas, although attempts have been made in recent years. This is mainly due to the paucity of gravity anomaly data sets and their rather poor distribution in the region.

The geoid is most commonly defined as the hypothetical equipotential surface of the Earth's gravity field, which would closely coincide with undisturbed mean sea level (MSL). Its determination remains as one of the basic task of ongoing researches in physical geodesy. This is because the majority of measurements are referred to Earth's gravity field. Traditionally its surface has served as the fundamental reference for orthometric height and its differences, gravity potentials and other vertical heights.

The importance contributions from the determination of the geoid can be summarised as follows:

- better understanding of the geology and the geophysics through geodetic perspective, since it is possible to study the gravity field features directly from the geoid, especially in areas of potential oil and gas bearing structures,

- greater use of GPS in height determination with high precision, since it has the potential to replace the costly, labourious and time-consuming spirit levelling,

- more accurate connection of one local vertical datum to another, especially for the control of levelling networks, and

- verification of apparent sea slope along the coasts.

3.1 GRAVITY NETWORKS

3.1.1 First Order Gravity Survey

The first order gravity survey was first carried out in 1988 and completed in April 1992 with a total of 180 points in Peninsular Malaysia (See Figure 3.1). The distribution is between 30 – 50 km along the Precise levelling Network with a misclosure of 30µgals. This network is known as the Peninsular Malaysia Gravity Standard Network 1989

(PMGSN'89). PMGSN'89 consists of standard benchmarks and other stations and is based on International Gravity Standard Network 1971 (IGSN71).

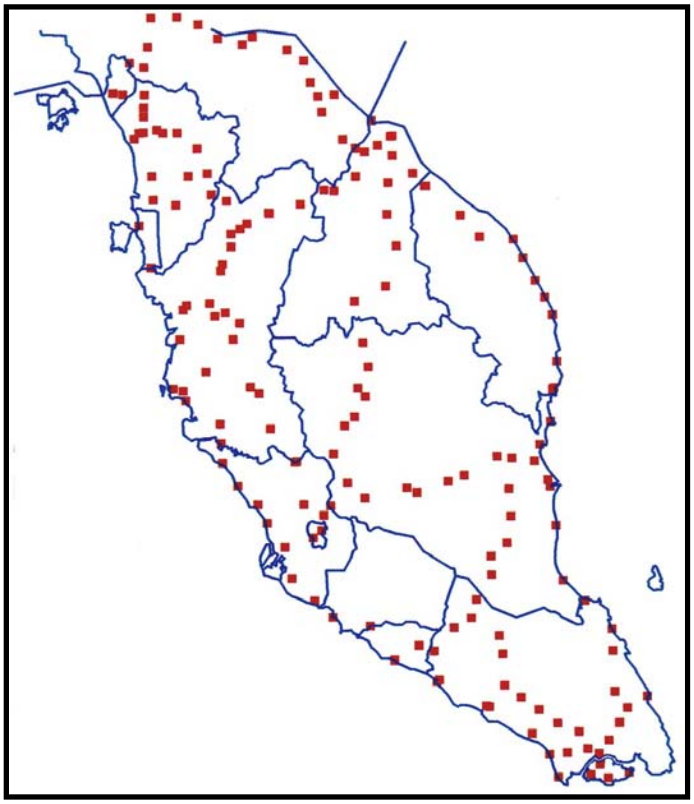


Figure 3.1 The Peninsular Malaysia Gravity Standard Network 1989 (PMGSN'89)

In 1998, a first order gravity survey named as Sarawak Gravity Standardisation Network (SSGSN) was established with a total of 56 points consisting of standard benchmarks and benchmarks (Figure 3.2). The interval between each station is between 15 – 25 km. The gravity reference datum was obtained from the Sabah and Sarawak Gravity Base Network UTM90, which was linked to IGSN71 (Figure 3.3). Another first order gravity survey network of 40 stations will be established in 1999 for the state of Sabah.

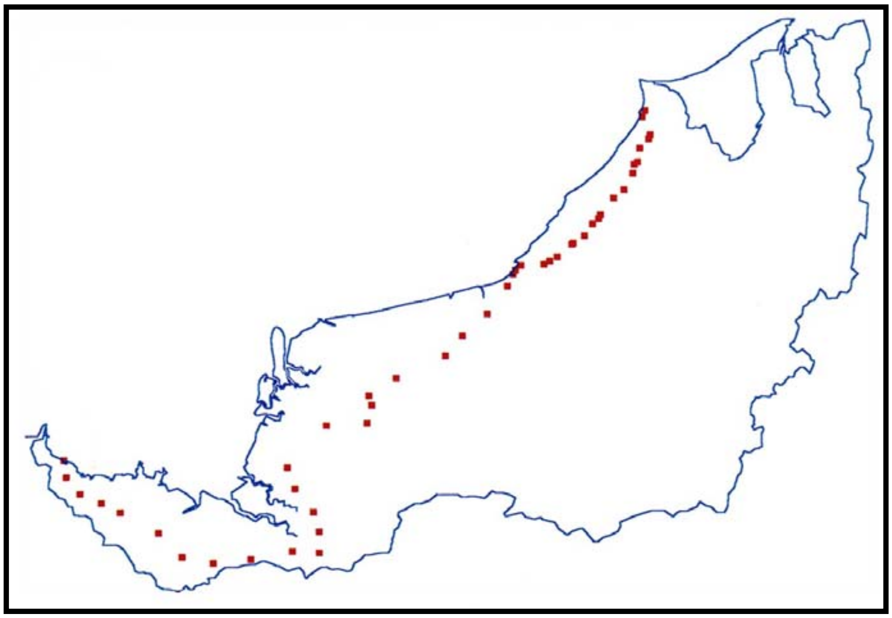


Figure 3.2 Sarawak Gravity Standardisation Network (SSGSN)

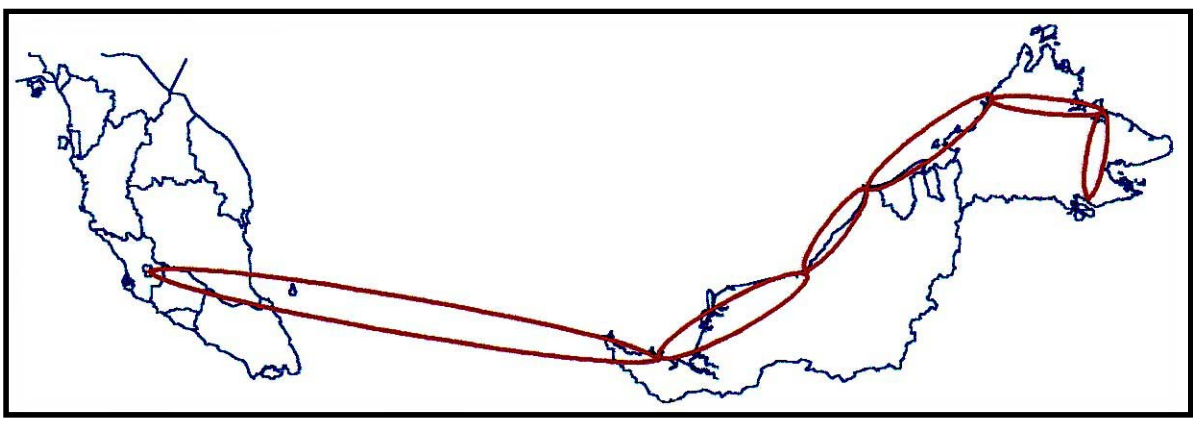


Figure 3.3 Sabah and Sarawak Gravity Base Network UTM90

3.1.2 Second Order Gravity Survey

The second order gravity survey was implemented in order to densify the points between the first order points. These points were positioned between the gravity stations from the first order points at interval of 5 km for low elevation and 1 km for elevation higher than 100 m above Mean Sea Level. The rejection criterion for misclosure is 50 μgals. To date, there are 1242 second order gravity points (Figure 3.4). These surveys were conducted for the purpose of applying orthometric corrections to the levelling network.

Figure 3.4 Second order gravity survey network

3.1.3 Third Order Gravity Survey

The third order gravity survey was started in 1994 by DSMM with the objective of establishing gravity points in gridded form at a density of 5-10 square kilometer per station. The accuracy of the misclosure is maintained at 100 μgals. A few problems were encountered during the field operations mainly due to inaccessibility such as rough terrain, swampy areas, bad and damaged road. Other problems are the unavailability of updated topography map and dense vegetation that hindered the progress of the fieldwork. To date, a total of 1410 third order gravity survey points has been obtained. The Geological Survey Department Malaysia (GSDM) has also contributed another 3895 gravity points in grid form at a density of 25 square kilometer per station with an accuracy of 100 μgals. The gravity data obtained from UTM consisted of 2921 stations, of which 1969 points are common with the data included in the DSMM and GSDM data set. Figure 3.5 shows the distribution of the third order gravity points.

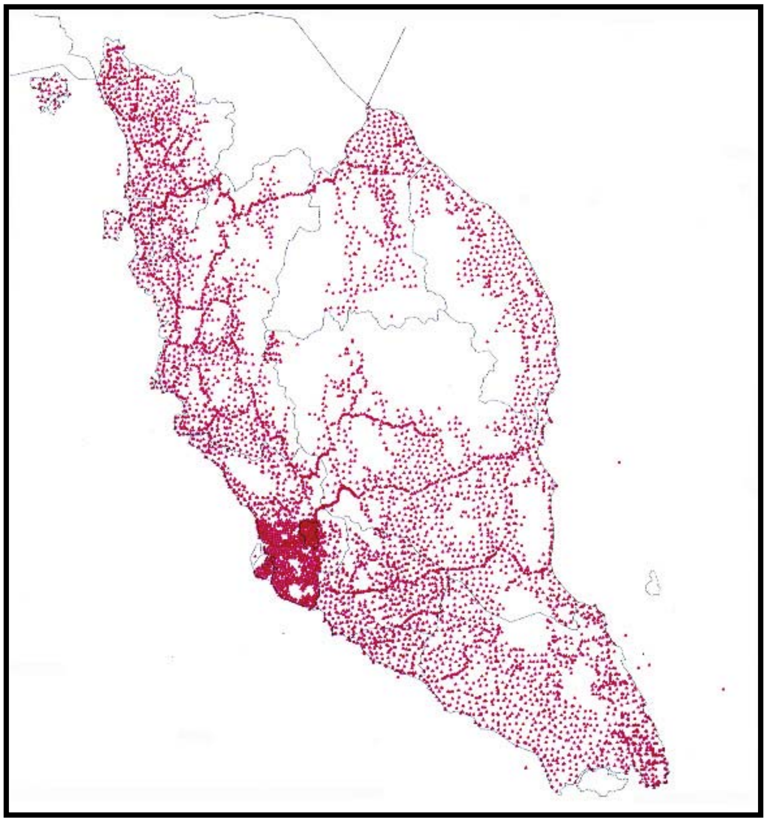


Figure 3.5 Third order gravity survey network

3.2 GRAVITY DATABASE

DSMM has formed a bank gravity database, which consists of collected data from various bodies and agents in the country that had conducted gravity surveys independently for various purposes. Among those agencies that had contributed to this database are DSMM, Geological Survey Department Malaysia (GSDM) and Universiti Teknologi Malaysia (UTM). DSMM had also obtained sea-borne gravity data from Bureau Gravimetrique Internationale (BGI) and satellite altimetry data from Geosat/ERM/GM and ERS-1/GM.

3.2.1 Gravity Data Format

In merging the various gravity data from different sources, one had to wrestle with the problem of different formats. In order to maintain the database in an orderly manner, the gravity data and free air anomalies are expanded back into observed gravity based on IGSN'71. The information is then stored as latitude, longitude (both in decimal degrees), observed gravity (mGal with the constant mGal subtracted) and height of station (m). Based on the format used by BGI, the format that has been agreed on is as follow:

DSMM Source Number	<8 characters>	e.g. GP0001
Station Name	<40 characters>	e.g. SRJK Convent Kelang
Latitude	<9 characters> (unit : 0.00001°)	
Longitude	<9 characters> (unit : 0.00001°)	

Observed Gravity <9 characters>(mGal)
Height <9 characters>(m)
System of Point Positioning <2 characters>

0=no information	1=First Order Gravity Survey
2=Second Order	3=Third Order
4=Fourth Order	5=Obs.being part of a nation's calibration line
6=Coastal Ordinary Observation	7=Harbour Base Station
8=Airborne Gravity Survey	

Determination of the Elevation <2 characters>

0=no information	1=First Order Levelling
2=Second Order	3=Third Order
4=Other Order	5=Trigonometric Levelling
6=Topographical Map	7=Barometric Levelling
8=Ellipsoidal Heights from GPS	

3.2.2 Sea-borne Gravity Data

Following the request from DSMM, BGI had provided 39,000 off-shore gravity values, extending from -4° to 13° in latitude, and 94° to 110° in longitude. Out of these, 29,662 ship-borne gravity measurements were extracted, and DSMM had retained 7,263 points in the gravity database (Figure 3.6).

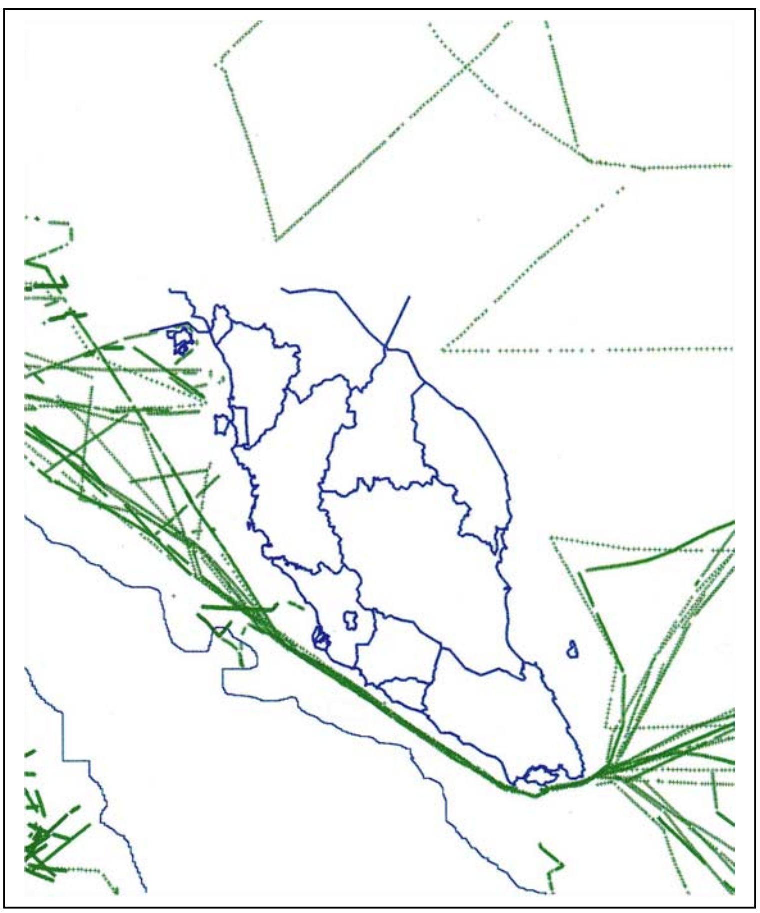


Figure 3.6 Sea-borne gravity data

3.2.3 Satellite Altimetry Data

A total of 27,122 free air anomalies, at a grid spacing of 2 minute (about 3.7 km), covering an area of $0° \leq \phi \leq 10°$ and $98° \leq \lambda \leq 106°$ was extracted from the global anomalies file gridded on a Mercator projection (Sandwell, 1982 and 1984; Smith and Sandwell, 1995). The data sources where the grid derived are: Geosat/ERM, Geosat/GM, ERS-1 and ERS/GM.

3.3 GEOID COMPUTATIONS

3.3.1 Malaysian Height Datum Project

The Investigation of Malaysian Height Datum (MHD) project was first proposed to DSMM in mid 1992 by the University of New South Wales (UNSW). After a review and detailed analysis of the available data and intensive discussions, the project was finally agreed upon in October 1993. The aim of the project is to use all current data relating to height control in Peninsular Malaysia such as tide gauges, conventional levelling, GPS heights and gravity data to produce an optimum height datum, height control system and geoid for the region.

The gravimetric geoid heights were evaluated by RING Integration method by employing gravity data in and around Peninsular Malaysia and the value obtained were compared with the GPS/Levelling via BAYCON (Bayesian Least Square and Constraint) adjustment.

Attempt had been made to produce the best possible geoid for Southern Peninsular Malaysia. The estimation of the precision of the gridded N data are mainly based on the results of the control, gravity coverage and topografic relief. This is tabulated in Table 3.1 and the division of the region into 32 blocks of 0.5 X 0.5 as in Figure 3.7. From Table 3.1, the precision varies from 1.5 ppm for flat areas and 9 ppm for mountainous regions. Thus, for areas with sparse gravity data, more measurements should be made and a reasonable good DEM must be produced for mountainous areas.

The importance outcome from this optimisation adjustment showed that the levelling network is internally consistent and there was no gross errors in this network. However UNSW identified that two important aspect to be resolved if the country want to fully used GPS technology for heighting and positioning:

i. Datum problem caused by quasi-WGS84 that the status of the datum used for the existing GPS network in Peninsular Malaysia.
ii. Significant variations in the quality of the geoid heights caused by the scarcity of gravity observations in some parts of this region.

When good coverage of gravity data becomes available, a more precise geoidal map can be produced to achieve centimeter level accuracy.

Table 3.1 Estimation of the precision of the gridded N data

1	2	3	4	5	6	7
Region	*Grid Block #*	*Gravity Coverage*	*Comments*	*Topo.*	*Comments*	*Precision (ppm)*
1	1	3	Satellite-Altimetry data offshore	2	Major river and delta	9
	2	3	Terrestrial	2	Slopes of Titiwangsa	9
	3	3	Terrestrial	3	Banjaran Titiwangsa	9
	4	2 to 3	Terrestrial	4	Banjaran Benum and valley	2 to 9
	5	2 to 3	Terrestrial	2	Tip of Banjaran Tahan	2 to 3
	6	2 to 3	Terrestrial	1 to 2	River delta	3
	7	2	Offshore. Mainly from Satellite Altimetry		-	
2	8	1 to 3	Sea-borne data offshore	1	Flat plains. Major River and delta	1.5 to 9
	9	1 to 3	Terrestrial	2 to 3	Slopes of Titiwangsa	1.5 to 2.5
	10	2 to 3	Terrestrial	3	Banjaran Titiwangsa	2.5
	11	2 to 3	Terrestrial	2	Daerah Bera	2 to 3
	12	3	Terrestrial	2	Daerah Pekan	3
	13	2 to 3	Offshore.-Mainly from Satellite Altimetry			
	14	1 to 3	Dense inland. Sea borne data offshore	1	Lembah Kelang. Delta	1.5
	15	1 to 2	Terrestrial with coastal effect	2	Lembah Kelang, Kuala Langat	1.5 to 2.5
	16	2	Terrestrial	3	Jelebu, Kuala Pilah	2.5
	17	2	Terrestrial	2	Daerah Jempol	2.5
	18	2 to 3	Terrestrial	2 to 3	Daerah Rompin, Banjaran Tahan	2.5
	19	3	Satellite-altimetry data offshore	1 to 2	Kuala Rompin	2.5
3	20	3	Offshore. Mainly sea-borne.	1 to 2	Mainly flat plains. Port Dickson	2.5
	21	2	Satellite- alt. and sea-borne offshore	2	Seremban, Rembau	2.5
	22	2	Terrestrial	1 to 2	Alor Gajah, Jasin, Melaka Tengah	2.5
	23	2 to 3	Terrestrial	2 to 3	Keluang, Banjaran Tahan	2.5
	24	2 to 3	Terrestrial	1 to 2	Daerah Mersing	3.5
	25	2 to 3	Offshore. Mainly satellite-altimetry	1	Tanjung Petai	3.5
4	26	2 to 3	Offshore. Mainly sea-borne	1	East Daerah Batu Pahat	2.5
	27	2	Terrestrial	2	Daerah Batu Pahat and Pontian	2.5
	28	2 to 3	Terrestrial	2 to 3	Kota Tinggi, north Johor Bahru	2.5
	29	2	Sea-borne and sat. alt. data offshore	1 to 2	East Kota Tinggi, Tangga 7	2.5
5	30	2 to 3	Some satellite-altimetry data offshore	1	Pontian Kecil	2.5
	31	3		1 to 2	Bandar Johor Baru, Tg. Kupang	2.5
	32	2 to 3	Sea-borne offshore	1		2.5

Classification of Gravity Coverage

1 Good with Dense Coverage
2 Medium Coverage
3 Poor Coverage

Classification of Topography

1 Marsh
2 Undulating to Hilly
3 Mountainous (< 2000 m)
4 Very Mountainous (≥ 2000 m)

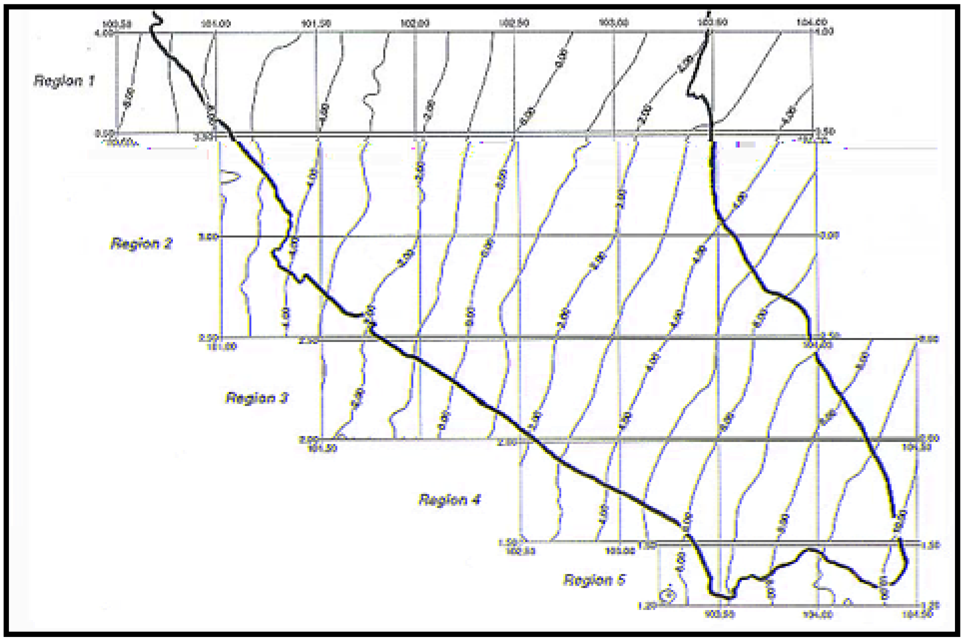


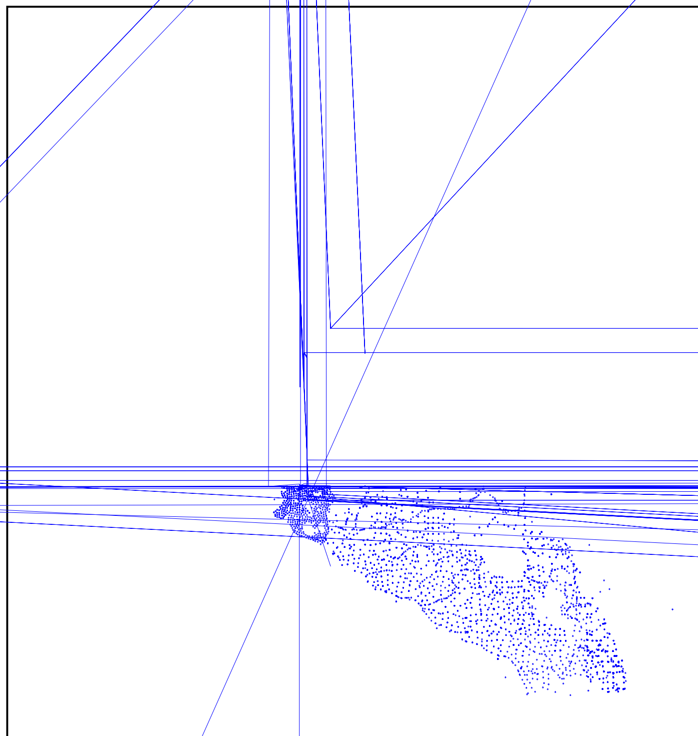
Figure 3.7 Southern Peninsular Malaysia gridded geoid map

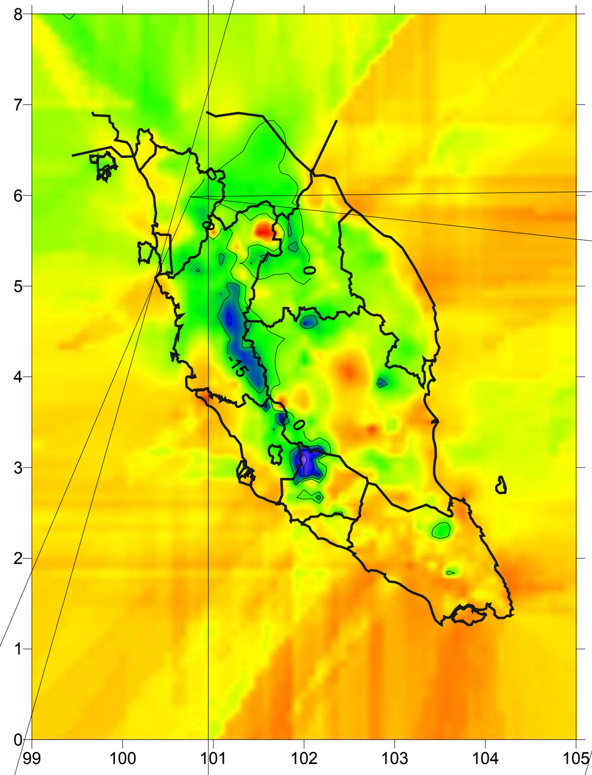
3.3.2 Preliminary Geoid Computation

In Peninsular Malaysia, the national gravity database is continuously being updated. The number of gravity points was less than 2000 in 1989. In 2000, the gravity database at DSMM has a total number of over 10000 points. The different types of data used to compute a preliminary geoid for Peninsular Malaysia are as follows:

- ***The EGM96 Global Geopotential Model:*** The most recent estimate of the global gravity field that is currently available is the Earth Gravity Model 1996 or EGM96. It is a global geopotential model in spherical harmonics complete to degree *l* and order *m* 360 (Lemoine *et. al.,* 1997) and considered as the best model currently available. Globally, EGM96 is estimated to give the geoid undulation with an accuracy of 1 m.

- ***Terrestrial gravity data:*** Generally, the gravity data over Peninsular Malaysia and the adjacent marine areas is poor. The data used in this study are 10400 point free air gravity anomalies which encompass the Peninsular Malaysia and surrounding marine area: $0° 00' N \le \phi \le 8° 00' N$ and $99° 00' E \le \lambda \le 105° 00' E$ (see Figure 3.8). The data belong to the DSMM Gravity Data Bank and are referenced to the International Standardisation Network 1971 (IGSN71).





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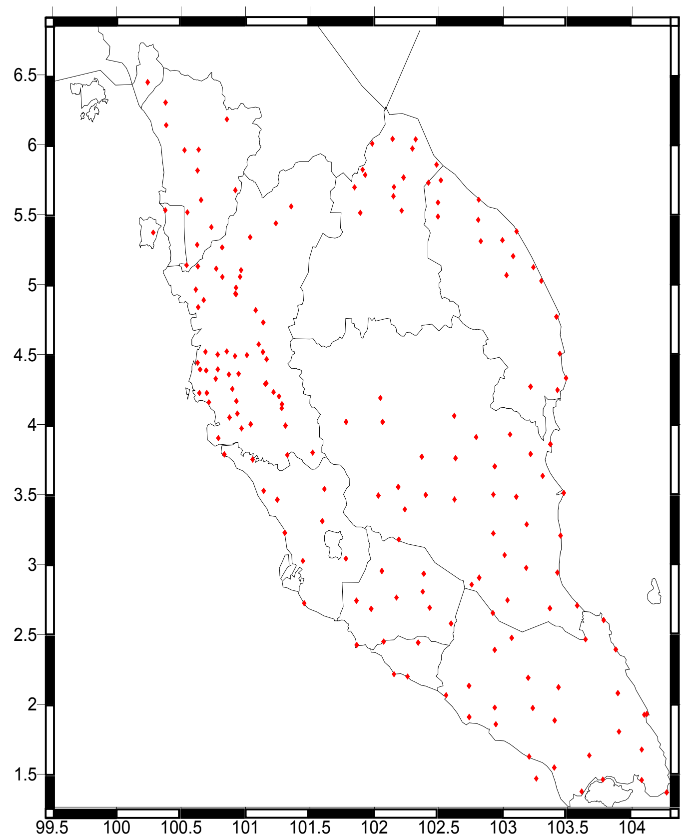


Figure 3.10 The distribution of 230 GPS points having both the ellipsoidal and orthometric heights to derive N_{GPS} and be compared with N_{GRAV} and N_{EGM96}

3.3.3.1 Geoid Computation Method

The gravimetric determination of the geoid at any point of geographical coordinates (φ, λ) essentially relies on the classical Stokes' Integral (Heiskanen & Moritz, 1967). This amounts to evaluating the integral for the sphere as follows:

$$N = \frac{R}{4\pi\gamma} \iint_{\sigma} S(\psi) \Delta g \; d\sigma \tag{3.1}$$

where R is the mean radius of the Earth, γ is the normal gravity on the GRS80 reference ellipsoid at the geodetic latitude of the computation point, Δg is the free-air gravity anomaly, dσ is the element of surface area for integration on the sphere and ψ is the angular distance between the point of computation and dσ, and *S(ψ)* is the Stokes' function of the angular distance ψ given by:

$$S(\psi) = \frac{1}{\sin\frac{\psi}{2}} - 4 - 6\sin\frac{\psi}{2} + 10\sin^2\frac{\psi}{2} - \left(3 - 6\sin^2\frac{\psi}{2}\right)\ln\left(\sin\frac{\psi}{2} + \sin^2\frac{\psi}{2}\right) \tag{3.2}$$

- **Computation Procedure**

The gravimetric geoid separation N can be computed by determining the long- and medium-wavelength contributions N_{egm} from the global geopotential model (GGM) coefficients of EGM96, the short- and part of the remaining medium-wavelength effect $N_{\Delta g}$ from terrestrial gravity data and associated height information N_h from a digital elevation model (DEM). This procedure is represented by the following relationship, such that:

$$N = N_{egm} + N_{\Delta g} + N_h \qquad (3.3)$$

The method used in this study breaks the gravity field into the three component and solve them separately. The "remove-compute-restore" technique (Schwarz *et. al.,* 1990) is one of the most commonly routine in computing regional gravimetric geoid nowadays. This technique requires the removal of spherical harmonic model (SHM) gravity anomalies before computing the Stokes' Integral, and the restoration of SHM geoid undulations following it.

The "remove-compute-restore" approach exploits the linear1M)tokes' Integral, and the restoration of SH

s o l v e m

where the operators F and F^{-1} denote the direct and inverse 1D discrete Fourier transforms respectively, $\Delta\varphi$ and $\Delta\lambda$ are the used latitudinal and longitudinal grid spacing, and φ_1 and φ_{max} are the southern and northern grid boundaries respectively.

Thus, the geoid undulation for all points on a parallel can be obtained.

iii. And finally, the last step is to *restore* back the effect of the EGM96 global geopotential model, N_{egm} (the long wavelength contribution) to the residual geoidal heights, $N_{\Delta g}$ and add the terrain effect term, N_H (computed from digital elevation model) to form the final geoid undulations.

Again from EGM96, the reference geoidal undulation N_{egm} or the long-wavelength geoid component was also made on a 2' x 2' grid within the geographical boundaries specified above. N_{egm} was computed using:

$$N_{egm} = R\sum_{n=2}^{360}\sum_{m=0}^{n}\left[C_{nm}\cos m\lambda_p + S_{nm}\sin m\lambda_p\right] P_{nm}\sin\phi_p \qquad (3.7)$$

3.3.3.2 Results and Comparisons with GPS/Levelling Heights

Figures 3.11 and 3.12 illustrate the contours of the EGM96 and preliminary national geoid model for Peninsular Malaysia (referred to here forth as MYGeoid02) respectively. It can be seen that both geoids are rising from north-west to south-east. Results also indicate that the maximum and minimum values of the MYGeoid02 are 9.45m and –14.66m respectively. Whilst for the EGM96 geoid, the figures are 9.53m and –14.47m. MYGeoid02 and EGM96 have a mean undulation value of 9.45m and 9.53m respectively.

GPS/Levelling geoid heights (N_{GPS}) for 230 points in Peninsular Malaysia are also computed by subtracting adjusted orthometric heights (H) from the corresponding GPS ellipsoidal heights (h) or simply (N_{GPS} = H – h). Comparisons are then made between the offset of EGM96 and MYGeoid02 models with these GPS-derived geoid height at each of those points. Table 3.2 shows descriptive statistics of the absolute fit of MYGeoid02 and EGM96 to the 230 GPS/Levelling control data.

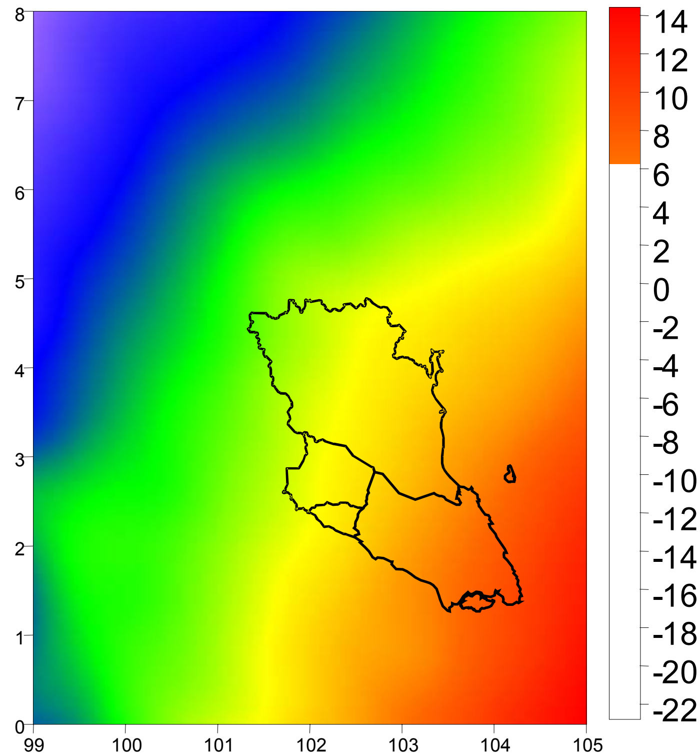


Figure 3.11 EGM96 geoid model for Peninsular Malaysia at 5-min grid

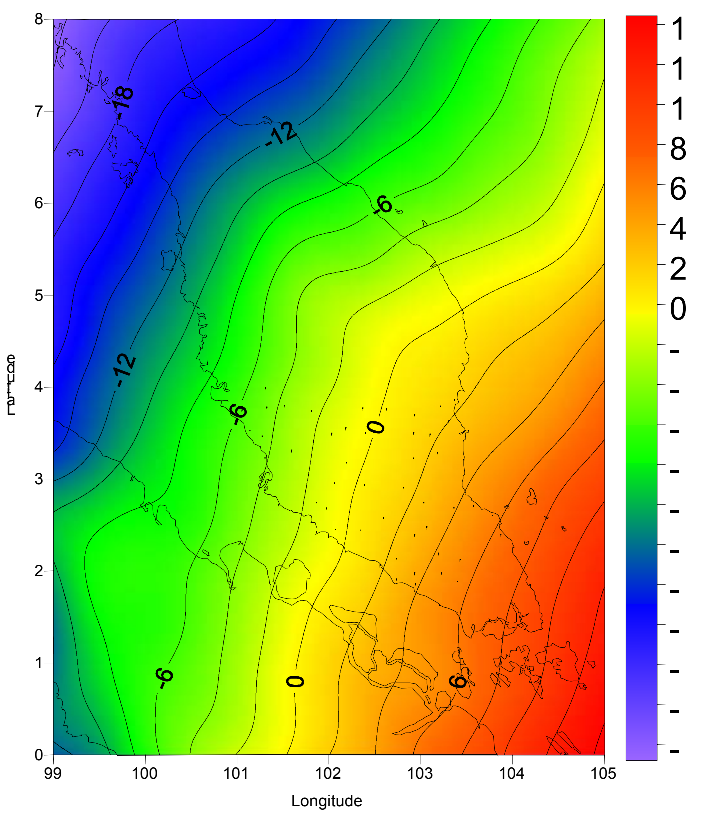


Figure 3.12 Preliminary geoid model for Peninsular Malaysia, MYGeoid02 at 2-min grid

The two geoid models are found to have approximately the same relative accuracy. Results show that the standard deviations of the differences are ±40 cm for the EGM96 solution and ±39 cm for MYGeoid02 solution. The 40 cm magnitude of the fit can be considered as satisfactory. From the inspection of the standard deviations of both geoids, it can be seen that MYGeoid02 represents only a slight improvement over EGM96.

Table 3.2 Comparison of geoid models to GPS-derived geoid (values in metres)

Geoid Model	$N_{Model} - N_{GPS}$			
	Minimum	**Maximum**	**Mean**	**Std. Dev.**
MYGeoid02	-0.943	0.688	-0.065	0.389
EGM96	-0.760	0.827	0.052	0.402

3.4 AIRBORNE GRAVITY PROJECT

The determination of a precise geoid at centimeter level accuracy for the Malaysian region has been hampered by the lack of gravity data. The gravity data for most parts is either very much lacking or not available at all. Terrestrial gravimetry is slow and very costly. On the other hand, airborne gravity technique is considered as the most efficient and fastest technique for gravity data acquisition with uniform coverage and consistent accuracy for the whole Malaysian region.

This technique has been established as a production system to accurately measure the gravity field of the earth from the air, using an aircraft as the measurement platform. Gravity data acquisition and geoid determination using heterogeneous data will provide Malaysia with state of the art technology in this field and ensure successful implementation of the project. The combination of airborne gravimetry data with terrestrial gravity measurement and other satellite gravity missions will further enhance the knowledge of the Earth's gravity field in the Malaysian region.

Currently, JUPEM publishes a preliminary geoid for Peninsular Malaysia that is thought to give an accuracy of around 0.4m. This is not sufficiently accurate to match what can be achieved by GPS heighting. In practice, the accuracy of the relative orthometric height ΔH is dependent on the accuracy of the geoidal height, ΔN, and the relative ellipsoidal height, Δh, in the relation:

$$\sigma_{\Delta H}^2 = \sigma_{\Delta N}^2 + \sigma_{\Delta h}^2 \qquad (3.8)$$

If the relative accuracy of Δh is taken as 2ppm over a line of 20km, the $\sigma_{\Delta h}$ inferred is 4cm. Similarly, if $\sigma_{\Delta N}$ is 5cm as a result of a 'hypothetical' improvement to our present geoid in Peninsular Malaysia – which is currently about 40cm level – the relative accuracy required for H is roughly 6.4cm. This equates to 3.2ppm.

Figure 3.13 shows a plot of the 3.2ppm line with the 1st and 2nd order levelling permissible discrepancy curves. It can be suggested that, with cm-accuracy geoid, the use of GPS in height surveys is comparable to 1st order levelling in not more than 1km. On the other hand, the technique exceeds 2nd order levelling for distances up to 15km. So if we can get our hands on a cm-geoid, these are the accuracies we will be dealing with when using GPS for orthometric heights determination.

Under the 8th Malaysia plan (2001-2005), JUPEM has initiated the Airborne Gravity and Geoid Mapping Project for the Peninsular Malaysia, Sabah and Sarawak. This project has been outsourced to a consortium, comprising of a local company and the National Land Survey of Denmark (KMS).

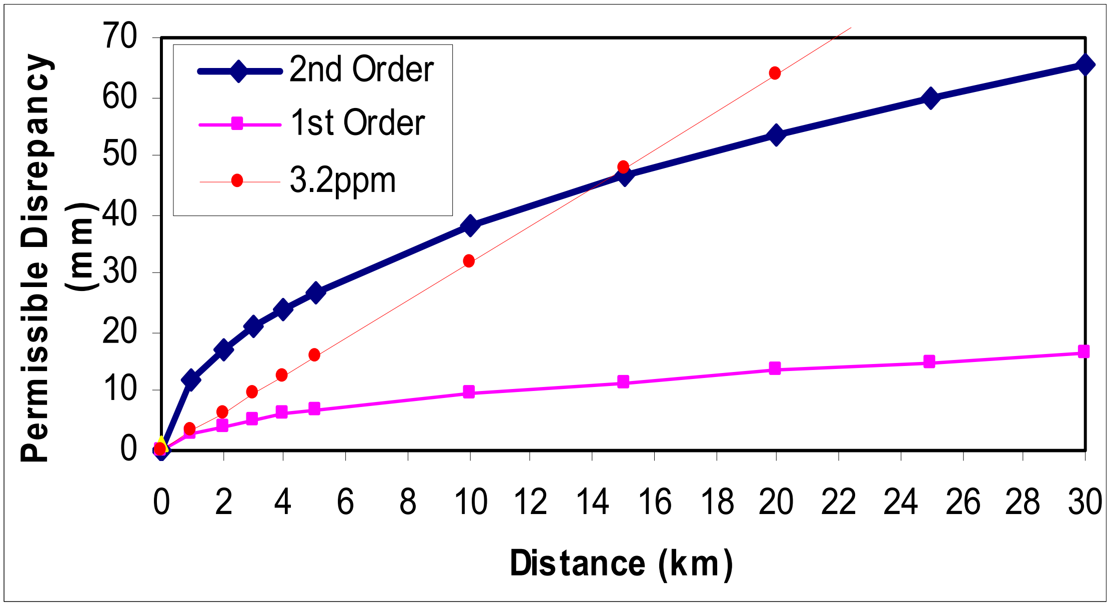


Figure 3.13 Comparison of accuracies of orthometric height differences from GPS (3.2ppm) and from spirit levelling

3.4.1 Objectives of the Airborne Gravity Project

The overall objectives of the project can be summarised as follows:

- To provide a dense gravity data at 2 mGal accuracy of gravity anomaly data at 5km spacing covering Sabah and Sarawak (Phase 1) and Peninsular Malaysia (Phase 2),

- To provide relative geoid accuracy of 5 cm and 1-2 ppm for the Malaysian region, and achieving accuracy using the acquired airborne gravity data and combination with the available terrestrial gravity data, other derived gravity data and digital terrain model, and

- To install processing hardware, airborne gravity processing software and geoid computation software at the Geodesy Section, Mapping Division, Department of Survey and Mapping Malaysia together with the training packages for the JUPEM personnel.

3.4.2 Project Implementation

- **Choice of Aircraft:**

A stable local aircraft with good autopilot and with good flight dynamic (phugoid motion) at low airspeed has been used (Figure 3.14). The aircraft must also meet the required specifications and include insurance coverage for survey personnel and equipments. It must have a Certificate of Air-worthiness (COA) from the Department of Civil Aviation, Malaysia (DCA).

Figure 3.14 The Aircraft

- **Equipments Used:**

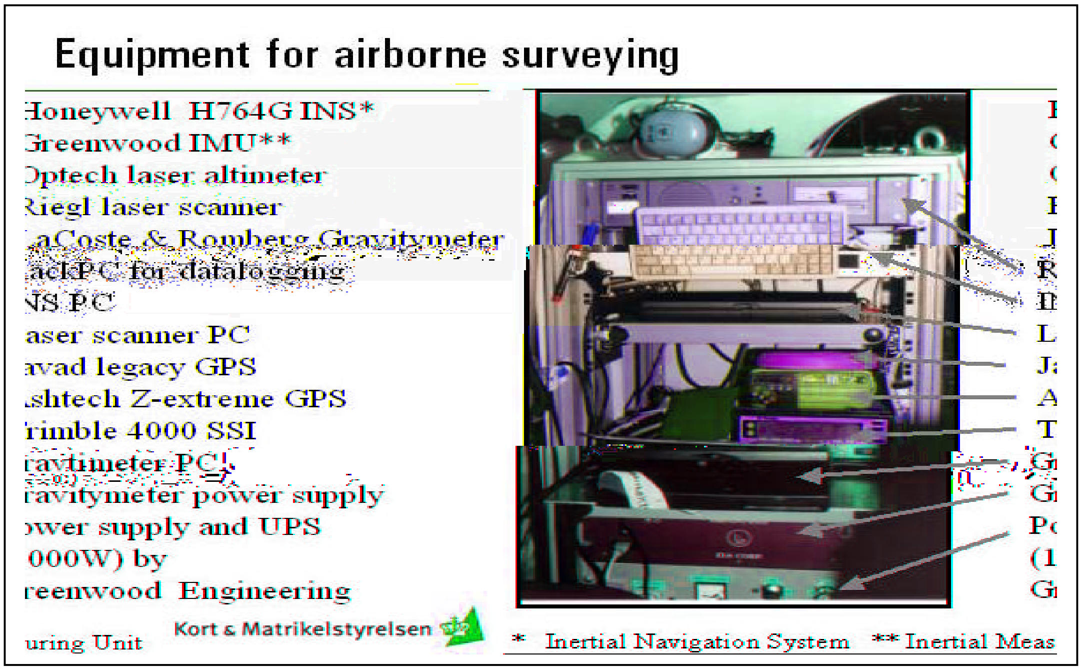
The gravimetry observation gadgets are stacked up as shown in Figure 3.15 below. These include:

a. Global Positioning System (GPS) instruments consisting of 3 types of GPS instruments inside the aircraft, namely Trimble, Ashtech and Javad with antennae mounted on top of the aircraft, 1 Trimble GPS as reference point near the airport and 1 GPS instrument at the MASS station as the backup reference point.
b. Inertial Navigation System (INS)
c. La Coste & Romberg Gravimeter
d. Computers and relevant peripherals and softwares.

- **Planning and Design of Survey:**

For the gravity survey, a 5 km spacing flight lines, which follow the shape of the area in order to obtain long flight lines for good survey design have been planned and executed. These lines are supplemented by cross-lines in order to assess the quality of the airborne gravity surveys. The Phase 1 of the airborne gravity survey which covers Sabah and Sarawak was started on September 2002. The planned flight lines for the airborne gravity survey are shown in Figure 3.16.

The flight lines are designed to embrace the entire length of Sarawak in the most economical way and time and a few cross-lines are design as a check. The flight lines are also prolonged so as to have a coverage extending 10 kilometers across the boundaries of the neighboring countries, Indonesia and Brunei. As for Sabah, the designed flight lines are much shorter following the shape of the state and there are more cross-lines involved which is more likely due to the vast variations in the


Equipment for airborne surveying
Honeywell H764G INS*
Greenwood IMU**
Optech laser altimeter
Riegl laser scanner
LaCoste & Romberg Gravitymeter
RackPC for datalogging
INS PC
aser scanner PC
avad legacy GPS
shtech Z-extreme GPS
rimble 4000 SSI
ravimeter PC
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* Inertial Navigation System ** Inertial Meas